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High-resolution physical properties, geochemistry and alteration mineralogy for the host rocks of the Archean Lemoine auriferous VMS deposit, Canada

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Abstract

Multi-parameter data on drill cores has a range of useful applications for ore deposit modeling and mineral exploration. Density, magnetic susceptibility, eight major elements, seven trace elements (portable X-ray fluorescence, pXRF), five mineral groups (near-infrared spectrometry) and average visible light reflectance were determined on rock cores from several drill holes. These are located near the Archean Lemoine auriferous volcanogenic massive sulfide (VMS) deposit in the Chibougamau mining district, Abitibi Subprovince, Quebec, Canada. This case study focuses on one drill hole in particular which has been recently characterized in detail by conventional methods (laboratory geochemistry, petrography, stable isotopes); this provides validation for the multi-sensor dataset. The best variables and immobile element ratios to distinguish between different lithological units in the multi-parameter data are density, magnetic susceptibility, Ti/Zr, Al/Zr, and Zr/Y. Downhole profiles of these parameters allow the four different felsic units in LEM-37, many of which are visually similar, to be distinguished, and geological contacts to be positioned precisely. Such methods would be even more useful in environments where recognition of primary characteristics is strongly hampered by intense hydrothermal alteration and superimposed deformation or metamorphism. Volcanic and intrusive rocks can be placed on classic diagrams to assign them names and magmatic affinities based on the corrected pXRF data. Downhole profiles of major and trace elements, combined with infrared mineralogy, allow hydrothermal alteration to be characterized, yielding results comparable to those of conventional techniques for the same drill hole, but with a much tighter spacing and within potentially shorter timeframes.

Keywords

Multi-parameter, physical properties, geochemistry, mineralogy, hydrothermal alteration, volcanogenic massive sulfide, Abitibi

Introduction

Advanced mineral exploration programs typically involve abundant diamond drilling. This is an expensive endeavor and the kilometers of drill cores produced are often not utilized to their full potential. Measurements of physical properties, geochemistry and mineralogy on drill cores have numerous potential applications, such as (1) planning and interpreting geophysical surveys, and integrating geology with geophysics; (2) gaining a better understanding of the geology of an area, through more consistent and homogeneous core logs, to target future drilling more efficiently; or (3) obtaining a three-dimensional picture of variations in hydrothermal alteration and using that to vector towards ore.

To build a large multi-parameter database for a certain region, it is possible to measure each property separately with various devices and laboratory techniques. However this is costly, time-consuming, and generally destroys much of the core if high spatial resolution (small measurement spacing) is required. Also with conventional whole-rock laboratory geochemistry, exploration geologists cannot readily integrate the analytical results in their core logs and drilling decisions since these results arrive weeks or months after the samples are sent out.

For high-resolution measurements of physical properties, geochemistry and mineralogy, one solution is to use a multi-sensor core logger (MSCL) housed in a mobile laboratory (Ross et al., 2013). The laboratory is utilized on core storage sites, and its non-destructive technology could potentially be used *before* geologists examine the cores and sample them, allowing for less subjective, more homogeneous core logs. In this study however the MSCL logging has been performed long after the visual logging. Specifically we have acquired MSCL data on several drill cores from the host rocks of the Archean Lemoine auriferous volcanogenic massive sulfide (VMS) deposit in the Chibougamau district of the Abitibi Subprovince, Quebec, Canada. This article focuses on one drill hole from the footwall of the deposit that has already been studied in great detail by more conventional field and laboratory methods (Mercier-Langevin et al., 2014), since this provides validation for the new multi-parameter dataset. We show that the downhole lithological discrimination can be improved, and hydrothermal alteration well characterized, with the MSCL data. In combination with a compilation of existing data, this leads to an enhanced understanding of the geological setting of the Lemoine deposit.

Geological setting

The Archean Abitibi Subprovince is a component of the Superior Province of Canada (Figs. 1a, b). The Abitibi Subprovince contains over 800 Mt of known VMS ore (Goutier et al. 2011; Mercier-Langevin et al. 2011), numerous orogenic gold deposits (e.g., Percival., 2007), and several other types of ores. The Lemoine auriferous VMS deposit is located in the Chibougamau mining district, in the NE corner of the Abitibi Subprovince (Fig. 1c). It was mined between 1975 and 1983 for a total production of 758,070 metric tons of ore at an average grade of 4.56 g/t Au, 4.17 wt % Cu, 9.51 wt % Zn, and 83.73 g/t Ag (Mercier-Langevin et al., 2014). These grades made it the second richest VMS deposit in Canada in terms of net smelter return (Riverin, 2003).

VMS deposits of the Chibougamau district are hosted in the >2730 Ma to ~2716 Ma Roy Group, which consists of two submarine mafic to felsic, volcanic to sedimentary cycles (Leclerc, 2011; Leclerc et al., 2011; David et al., 2012 and references therein). The base of the first cycle consists of mafic lavas of the 3-4 km-thick Obatogamau Formation that are overlain by the several hundred meters-thick felsic-dominated Waconichi Formation (2730 Ma to 2726 Ma; Mortensen, 1993; Legault, 2003; Leclerc et al., 2011; David et al., 2012). The Waconichi-hosted VMS deposits are therefore classified as bimodal-mafic. Lemoine and the other known VMS deposit of the Chibougamau district, Scott Lake (Saunders and Allard, 1990; Carignan, 2010; inferred resources of 5.4 Mt grading 4.6% Zn, 1.2% Cu, 0.2 g/t Au, and 34 g/t Ag: Salmon and McDonough, 2011) are both associated with F_{III}-type quartz-phyric felsic volcanic rocks of the Waconichi Formation (Daigneault and Allard, 1990).

Methods

The cores from six diamond drill holes from the Lemoine area were analyzed with a multi-sensor core logger (MSCL) housed in a mobile laboratory. We focus here on drillhole LEM-37, the collar of which is located about 600 m WSW from the former Lemoine Mine (Fig. 2). This drill hole and another to the NE of the mine, LEM-40, were studied in great detail by Mercier-Langevin et al. (2014), who utilized visual core logging, petrography, traditional (laboratory) whole-rock geochemistry, electron microprobe analyses, and whole-rock oxygen isotopes to study the lithology and hydrothermal alteration in the host rocks of the Lemoine auriferous VMS deposit. This provides abundant conventional data from the same drill core (LEM-37) with which to compare the MSCL results. Other existing data that was compiled include several hundred whole-rock geochemical analyses from industry spread over the Lemoine property; these were used to establish the geochemical signature of each unit (Ross et al., 2014a).

The MSCL is a semi-automated system that can measure near-simultaneously, non-destructively, and at high spatial resolution, the following parameters: (1) volumetric magnetic susceptibility, (2) density using gamma-ray attenuation, and (3) visible/near infrared spectrometry, which allows numerous hydrothermal alteration (and primary) minerals to be detected and characterized. A reflectance log can also be extracted using the average value in the visible light range: 0% is black and 100% is white. We use two portable X-ray fluorescence (pXRF) analyzers separately from the MSCL to save time during data acquisition: one measuring major elements, and the other measuring trace elements. The pXRF data is corrected after acquisition, in a spreadsheet, to remove systematic errors as much as possible. The corrections are element- and device-specific; they are based on equations derived from plots of pXRF versus traditional geochemistry for a range of mafic to felsic volcanic and intrusive samples from the Abitibi Subprovince. The logger also acquires a continuous image of the core using a line-scan camera. Our methods have been described in detail by Ross et al. (2013, 2014b, 2014c) and references therein, with recent improvements for geochemistry presented by Bourke and Ross (2015).

LEM-37 is a 894.2 m-long BQ (3.7 cm diameter core) drill hole; the cored portion starts at 5.5 m, for a total core length of 888.7 m. We have obtained a total of 3486 measurements of density, magnetic susceptibility, and infrared spectrometry in this hole, for a downhole resolution (average measurement spacing) of 25.5 cm. In addition we have determined eight major elements and seven trace elements on every other spot, for a total of 1757 geochemical measurements. The data is available from the first author upon request.

Refinement of the local geology and lithogeochemistry

Based on the compilation of existing data, and the new multi-parameter dataset, the primary geochemical signature of each major unit in the Waconichi Formation has been established for the Lemoine mine area (Ross et al., 2014a), and a composite vertical cross-section has been drafted ~0.6 km WSW of the former Lemoine Mine, along line 2200W on the local grid (Fig. 2). The composite section was placed there in order to obtain a complete section from the synvolcanic Lac Doré Complex in the NNW (footwall) to the Stella Formation in the SSE (hanging wall), which would not have been possible closer to the mine given the available drill holes.

In the Lemoine area, volcanic rocks belong to the Lemoine Member of the Waconichi Formation. This member has been informally divided into a felsic-dominated lower part and a mafic-dominated upper part (Fig. 2). Based on trace element ratios such as Zr/Y and Th/Yb, magmatic affinity is tholeiitic to transitional in the lower part and transitional to calc-alkaline in the upper part (Lafrance and Brisson, 2006; Mercier-Langevin et al., 2014; Ross et al., 2014a; Boulerice, 2016). The Lemoine deposit ore horizon is situated at the contact between the two parts of the Lemoine Member, more specifically between the Lemoine Rhyolite in the footwall and the hangingwall quartz feldspar porphyry (HWQFP) (Riverin, 2003; Mercier-Langevin et al., 2014).

The composite cross-section shows the trace of drill hole LEM-37and two other drill holes also studied with the MSCL (LEM-46 and LEM-59, including its extension LEM-59E; Fig. 3). The volcanic and sedimentary rocks young to the SSE and dip steeply in the same direction. From NNW to SSE, the geological units visible in this cross-section are:

- the synvolcanic Lac Doré Complex, a mafic layered intrusion, more specifically the uppermost Granophyre Zone and the Border Zone (Daigneault and Allard, 1990);
- a quartz-phyric intrusion which might be related to the Granophyre Zone;
- the lower part of the Lemoine Member (Waconichi Formation), here dominated by the Lemoine Rhyolite that is overlain by the Lemoine Andesite;
- the upper part of the Lemoine Member (Waconichi Formation), with the HWQFP at the base, overlain by a thick succession of transitional basalts;
- the <2704 ± 2 Ma Stella Formation of the Opémisca Group, which sits unconformably above the Roy Group rocks, and consists of sandstones, conglomerates, and finer-grained sedimentary rocks (Daigneault and Allard, 1990; Leclerc et al., 2012).

In addition there are several intrusive units cutting the Lemoine Member (Fig. 3): the Marelle QFP, the Lemoine Diorite (Lafrance and Brisson, 2006), the Coco Lake Rhyolite (formerly named the Upper Lemoine Rhyolite: Boulerice et al. 2013, 2015), and minor gabbroic intrusions.

Some more details are now given for the geological units encountered in LEM-37 specifically, based on existing and new data. The Lemoine Rhyolite consists mostly of massive and lobate rocks, with minor hyaloclastite, and is interpreted as effusive. Volcaniclastic rocks are more abundant near the top (Mercier-Langevin et al., 2014). The Lemoine Rhyolite contains 2-5% quartz phenocrysts 1-2 mm across in a fine groundmass, or it can be nearly aphyric in hand sample (Lafrance and Brisson, 2006).

The Marelle QFP is a massive homogeneous intrusive unit. It contains abundant coarse phenocrysts: 2-10% bluish quartz (2-6 mm) and 3-10% feldspar (1-5 mm) in a finer groundmass (Lafrance and Brisson, 2006). The Coco Lake Rhyolite is another quartz- (7-8%, 1-2 mm) and feldspar-phyric (3-5%, 1-3 mm) unit (Boulerice et al., 2013, 2015). It is massive and it occurs at different stratigraphic positions.

The HWQFP contains abundant coarse bluish quartz (5-10%, 3-8 mm) and feldspar (10-20%, 2-5 mm) phenocrysts (Lafrance and Brisson, 2006). Locally the crystal content reaches 30-40% (Riverin, 2003) and some previous authors interpreted this unit as a crystal tuff (e.g., Lavallière, 1994). Regionally the HWQFP can be up to 175 m-thick, and can contain lobes and large amygdales, making it in part effusive. In LEM-37 however, it is volcaniclastic and much thinner (Mercier-Langevin et al., 2014).

The Lemoine Diorite is a dioritic to gabbroic intrusion which cuts the volcanic strata at a low angle (Fig. 3). It is strongly foliated and it can be quite hydrothermally altered in the mine area (Mercier-Langevin et al., 2014), which suggests an early emplacement. However the map (Fig. 2) and composite section (Fig. 3) show that the Lemoine Diorite invades the transitional basalts of the upper Lemoine Member, which would make it younger than previously thought, although still synvolcanic.

Multi-parameter data in LEM-37

Figures 4 to 7 show downhole profiles for all the parameters measured with the MSCL in LEM-37. The profiles are useful to distinguish between different lithologies, and help characterize hydrothermal alteration in terms of composition and distribution.

Characterizing lithologies and locating geological contacts

The best variables and ratios to distinguish between different lithological units and locate geological contacts in the MSCL dataset are density, magnetic susceptibility, and the Ti/Zr, Al/Zr and Zr/Y ratios (Fig. 4). The average visible light reflectance profile is also of some use (mafic rocks being typically darker than felsic rocks), although it is influenced by hydrothermal alteration. Ratios of typically immobile elements are generally less susceptible to modifications during hydrothermal alteration and the chosen elements for these ratios (Al, Ti, Y, Zr) are satisfactorily analyzed by pXRF.

The physical properties depend on both protoliths and alteration, but are still useful for lithological discrimination: mafic rocks are generally denser than felsic rocks, and magnetic susceptibility is often (not always) higher in intrusive rocks than in volcanic rocks in the Lemoine sector. Magnetic susceptibility versus density were plotted on Figure 8 for a subset of data points from LEM-37. The Lemoine Rhyolite has a low density (mostly in the 2.65-2.90 g/cm^3 range) and a low magnetic susceptibility (mostly in the range 10-70 x 10^{-5} SI). Data points identified as Lemoine Rhyolite in the original company core log but with higher densities or susceptibilities are interpreted as dikes; this is confirmed by anomalously high Ti/Zr and Al/Zr values (Fig. 4), as well as low SiO_2 values (Fig. 5) (see the "D" annotations on Fig. 4 and the "GGil" subunits in Mercier-Langevin et al., 2014).

The Coco Lake Rhyolite and the Marelle QFP units have a low density (mostly in the 2.70-2.75 g/cm^3 range) and magnetic susceptibility values up to 2000 x 10^{-5} SI, several orders of magnitude higher than the Lemoine Rhyolite. However, the lowest values of magnetic susceptibility for the Coco Lake Rhyolite and the Marelle QFP overlap with those of the Lemoine Rhyolite, so physical properties must be used alongside geochemical ratios to separate the units apart.

The Ti/Zr and Al/Zr ratios provide indications on magmatic differentiation (Figs. 4, 9). High values correspond to mafic rocks, whereas low values correspond to felsic rocks. Using both ratios together adds discriminating power, since units that have similar Ti/Zr ranges can sometimes be distinguished by their Al/Ti ratio (e.g., Ross et al., 2014c). The Nb/Y ratio indicates the subalkaline nature of the rocks (Winchester and Floyd, 1977) (Fig. 9a), and can add discriminating power too, although Nb is below detection limit for some mafic rocks in the pXRF data. On the Ti/Zr versus Al/Zr diagram (Fig. 9b), the three felsic units in the footwall of the Lemoine VMS deposit (Lemoine Rhyolite, Marelle QFP, Coco Lake QFP) plot as distinct groups, although there is some overlap.

The Zr/Y ratio is a proxy for magmatic affinity (Barrett and MacLean, 1999; Ross and Bédard, 2009). On a Zr versus Y diagram (Fig. 10), the Coco Lake Rhyolite, Marelle QFP and the Lemoine Rhyolite have low Zr/Y values, plotting as tholeiitic units. The Lemoine Rhyolite is characterized by much higher Zr and Y contents than the other two felsic units (see also Fig. 6). In contrast, the Lemoine Diorite and the mafic dikes contain less Y than the felsic units and plot mostly in the transitional field. The HWQFP also plots mostly in the transitional field (Fig. 4), contributing to distinguishing it from other felsic units.

Using the physical properties, immobile element ratios, and elemental abundances together is ideal to precisely position contacts between major units in the drill hole or to identify dikes within the major units. For example, the transition from the Lemoine Rhyolite to the Marelle QFP at 561.6 m is marked by an increase in magnetic susceptibility (especially in the lower part of the Marelle interval) and Ti/Zr (Fig. 4), but a decrease in Nb, Y and Zr (Fig. 6). In this particular case the contact can also be located visually due to a change in phenocryst content, but such data would be particularly valuable to separate visually similar units, or in situations where intense hydrothermal alteration, deformation or metamorphism have destroyed primary textures.

There is a general correspondence between the pXRF composition of the gabbros in LEM-37 and the geochemical field compiled for the transitional basalt (based on conventional geochemistry) on several graphs; this supports the idea that these gabbroic intrusions are feeder dikes for the transitional basalt in the upper part of the Lemoine member (Mercier-Langevin et al., 2014). Variations in geochemical and magnetic susceptibility profiles for the Lemoine Diorite suggest that it comprises several intrusive phases (Figs. 4, 5, 6).

Hydrothermal alteration

Downhole profiles of mobile major and trace elements are useful indicators of hydrothermal alteration and its effects on the rocks (Figs. 5, 6). For example, Fe is more abundant in the lower part of the Lemoine Rhyolite (below 612.2 m) than in the upper part, and Mg is always below the limit of detection in felsic rocks in LEM-37, except from about 820 m downward. The increase in Fe and Mg corresponds to a greater abundance of chlorite (with the Mg numbers influenced by chlorite compositions, which are variable in this system). Conversely, Ca is detected in felsic rocks above 612.2 m, but very rarely below (Sr also becomes lower), corresponding to a general decrease in carbonate abundance with depth. The highest K and Rb values in the upper part of the felsic package (Figs. 5, 6) correspond to greater sericite abundances closer to the ore horizon (Mercier-Langevin et al., 2014).

The main mineral groups detected by infrared spectrometry in LEM-37 are chlorites, white micas, carbonates, epidote, and amphiboles (Fig. 7). The last two mineral groups are largely restricted to mafic intrusions in LEM-37, and are interpreted as probably metamorphic in origin. The first three groups (chlorites, white micas, carbonates) give indications on hydrothermal alteration conditions and zonation, especially in felsic rocks.

Three main pervasive and widespread alteration assemblages were reported by Mercier-Langevin et al. (2014) in the Lemoine Rhyolite (Fig. 7, circled numbers in right margin):

(1) a semi-concordant sericite-carbonate assemblage, poor in chlorite, from the top of the unit (162.6 m) to about 510 m [5-20% sericite, 3-20% carbonate (ankerite, siderite, parisite-synchisite), ≤5% chlorite];

(2) a semi-concordant to discordant sericite-chlorite assemblage, poor in carbonates, between ~510 m and ~610 m [10-20% sericite, 10-20% chlorite, ≤2% carbonate (ankerite)]; and

(3) a concordant to slightly discordant chlorite-sericite-chloritoid assemblage, without carbonate, between ~610 m and ~830 m [10-20% chlorite, ≤15% sericite, ≤4% chloritoid].

A forth alteration assemblage, forming discordant bands cm- to a few m-thick cross-cutting the other assemblages, consists mostly of chlorite (40-60% chlorite, 10-20% sericite, ≤10% calcite). Among the three pervasive assemblages, the third (chlorite-sericite-chloritoid) has the highest Ishikawa alteration index values (Fig. 7).

Overall, the same response is obtained with infrared spectrometry, taking into account the limitations of the method, such as high detection limits. The top of assemblage 1 shows white mica as the main mineral (black lines on Fig. 7) and carbonate as the secondary mineral (red squares); chlorite is not detected or forms the secondary mineral. Lower in assemblage 1, chlorite increases, and sometimes becomes the dominant mineral. Assemblage 2 is characterized by a mixture of chlorite, white mica and carbonate. Finally, assemblage 3 has no carbonate; chlorite is the main mineral and sericite is the secondary mineral. Chloritoid was not detected by infrared spectrometry due to its low abundance.

Discussion

The sensors and instruments employed in the INRS multi-sensor core logger are not new, but measuring magnetic susceptibility, density, geochemistry and mineralogy on exploration drill cores with a single mobile laboratory is a first to our knowledge. Alternative core logging or imaging systems exist in academic and commercial settings (some are reviewed and compared by Ross et al., 2013), but they do not integrate all of these parameters. Although in this study we have performed our measurements on drill cores that were several years old, it should be possible to integrate the multi-parameter logging in the exploration workflow *before* the visual description by geologists. The project described here was done in a VMS setting, but the parameters measured would likely be equally useful in other contexts such as epithermal or porphyry exploration and mineral deposit research.

Multi-parameter data on exploration drill cores has several possible useful applications. Physical property measurements are essential to constrain geophysical inversions (e.g., Spicer et al., 2011; Tavakoli et al., 2012), or to generate mineral prospectivity maps (e.g., Hayward et al., 2013). Density and magnetic susceptibility help discriminate between different lithologies, especially when combined with geochemical data (Ross et al., 2013; this study). In drill hole LEM-37, the three felsic units from the footwall of the Lemoine VMS deposit, which in some cases are visually impossible to distinguish, have distinct physical properties. More specifically, the two intrusive felsic units (Coco Lake Rhyolite and Marelle QFP) have magnetic susceptibilities that are up to two orders of magnitude higher than those typical of the extrusive felsic unit (Lemoine Rhyolite). Mafic dikes cross-cutting these felsic units are characterized by higher densities.

High-resolution geochemistry using pXRF technology is useful to distinguish units and precisely locate lithological contacts, especially in geologically challenging environments (intense alteration, tectonic deformation, metamorphism). A spatial resolution of 0.5 m or less can be obtained for pXRF downhole profiles, compared with a 10-50 m sampling interval for traditional geochemistry. The latter data are generally more precise and accurate, and also more complete (more elements), which allows for a complete characterization of the rocks, but is expensive and associated with significant delays in getting the data. pXRF data allow very precise positioning of contacts between units, even in the presence of hydrothermal alteration, as measurement spacing can be adjusted to the necessary level of detail. Better distinguishing between units, visualizing their internal variations, and positioning contacts leads to better cross-sections and geological maps, which are essential to understand volcanic stratigraphy and architecture when exploring for VMS and other volcanic-hosted deposits. For example, in the composite section compiled for this study (Fig. 3), having pXRF data available meant that the lens of Lemoine Andesite in LEM-46, and the altered quartz-phyric intrusion in LEM-59E, could be more confidently added to the interpretation.

The data spread on binary diagrams of geochemical ratios is greater with pXRF data than for traditional geochemistry, even with data smoothing, due to a smaller amount of material being analyzed. But geological contacts are identified on downward profiles, not binary diagrams. We show here that smoothed (with three-point moving averages) and corrected pXRF data can be used to differentiate geological units on Winchester and Floyd (1977) diagrams, and to get an idea of the magmatic affinity on Zr versus Y diagrams. Ross et al. (2014c) has already demonstrated that in the Matagami district, pXRF data allowed the rapid distinction of two visually similar and variably altered felsic units, based on a Ti/Zr versus Al/Zr diagram. The importance of making such a rapid distinction there was that the target horizon for VMS mineralization in Matagami is sometimes located at the contact between two visually very similar felsic units. The Ti/Zr versus Al/Zr diagram is very effective at Lemoine and helps distinguish the three felsic units in the footwall. However there is some overlap between units on the diagram, signaling the need to acquire pXRF data points on several spots along the core to confidently assign a lithology.

Another use of pXRF data is characterization and mapping of hydrothermal alteration, although for this exercise, infrared spectrometry is the most powerful tool as it directly provides the relative (semi-quantitative) abundances of the main alteration minerals. Mercier-Langevin et al. (2014) has shown using traditional methods (petrography, whole-rock geochemistry, oxygen isotopes) that within the Lemoine Rhyolite – the effusive footwall of the Lemoine deposit – the upper portion has low-temperature (<200°C) carbonate-sericite alteration in LEM-37. Moving downward in the Lemoine Rhyolite, they describe a high-temperature (>300°C) sericite-chlorite (low-carbonate) assemblage, and finally a high-temperature (>350°C) chlorite-sericite-chloritoid assemblage. The infrared mineralogy presented here is in good agreement with these findings. Relative to a traditional laboratory-based study such as that performed by Mercier-Langevin et al. (2014), infrared mineralogy provides more rapid information, is not destructive, and has a much higher spatial resolution if desired. It can also potentially be made available during core logging, instead of being performed months or years later.

Conclusions

Multi-sensor core logging has long been used in scientific drilling, but this is one of the first times that it is applied to studying the host rocks of ore deposits. Portable XRF (pXRF) analyses, which are included in this study, are gaining popularity in mineral exploration, not only to estimate concentrations of ore elements (e.g., Fajber and Simandl, 2011), but also to study the rocks enclosing the mineralization (e.g., Gazley et al., 2011, 2014; Ross et al., 2014c; Piercey and Devine, 2014). While pXRF on its own is definitely useful, combining it with measurements of physical properties and infrared mineralogy provides a more complete characterization of the drill cores. These additional parameters can be included in multivariate statistical analyses along with the pXRF data to discriminate between lithologies (e.g., Fresia, 2013), can be used for geophysical applications, or to characterize hydrothermal alteration around ore deposits. Such applications can lead to better targeting for future drilling.

In this study we have examined downhole profiles of density, magnetic susceptibility, three immobile element ratios, eight major elements, seven trace elements, five mineral groups and the average visible light reflectance all determined on the same core measurement points for a drill hole, LEM-37, located near the Lemoine auriferous VMS deposit. Several other drill holes were also analyzed in the same manner in the Lemoine area, including two on the same composite cross-section as LEM-37. Combined with a compilation of existing data this leads to the following conclusions:

1. The composite cross-section shows some previously unrecognized or unpublicized geological features, including a quartz porphyry intrusion between the Lac Doré Complex and the Lemoine Rhyolite, a lens of Lemoine Andesite at the top of the Lemoine Rhyolite, and the fact that the Lemoine Diorite cuts into the transitional basalts in the upper part of the Lemoine Member;
2. The combination of physical properties and pXRF data can successfully distinguish between the four different felsic units present in LEM-37 (Lemoine Rhyolite, Marelle QFP, Coco Lake Rhyolite, hanging wall QFP); contacts between units that are sometimes visually very similar are precisely positioned;
3. Geochemical classification diagrams can be used quite reliably with corrected and smoothed pXRF data;
4. The pattern of hydrothermal alteration in the Lemoine Rhyolite, i.e. in the footwall of the Lemoine VMS deposit, has been characterized in LEM-37 by infrared spectrometry and pXRF with results similar to those obtained by more conventional laboratory techniques, but at higher spatial resolution;
5. Infrared spectrometry can identify and semi-quantify fine-grained alteration minerals that are difficult or impossible to recognize with the naked eye.

Multi-parameter databases are *not* meant to replace the core-logging geologist and traditional geochemistry analyses, but instead should be seen as additional useful data for geological and geophysical interpretations. They can help to create more consistent and homogeneous core logs. Future work will attempt to use gradients in hydrothermal alteration, including compositional variations within minerals, to vector towards ore.

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Figures

Fig. 1. (a) Location of the Abitibi Subprovince in eastern Canada. (b) Simplified geology of the Abitibi Subprovince showing the location of the Chibougamau district. (c) Simplified geology of the Chibougamau district (modified from Leclerc et al., 2012) showing the location of the two known VMS deposits, Scott Lake and Lemoine, in felsic rocks of the Waconichi Formation.

Fig. 2. Geology of the area around the former Lemoine Mine. The VMS deposit is shown in red, south of the former shaft site; mineralization sat at the top of the Lemoine Rhyolite, under the HWQFP. The trace of the composite section shown in Fig. 3 (along line 2200W) is marked. Map modified from Lafrance and Brisson (2006), Mercier-Langevin et al. (2014) and Boulerice (2016); U-Pb ages from Mortensen (1993).

Fig. 3. Composite vertical cross-section along line 2200W (0.6 km WSW from the former Lemoine mine), compiled with information from Cogitore Resources Inc (existing cross-sections, core descriptions, whole-rock geochemistry) and the MSCL data. Drill holes have been projected laterally by up to 550 m, explaining some distortions in the contacts. Drill holes shown in blue have been logged with the MSCL. Modified from Ross et al. (2014a).

Fig. 4. Downhole variations in physical properties, average visible light reflectance, and three ratios of immobile elements (corrected pXRF data) in LEM-37. A logarithmic horizontal scale has been used for magnetic susceptibility, Ti/Zr and Al/Zr. "n.d." means "no data", and intervals marked "D" are interpreted as dikes (underlined if noted in the original core description). For figures 4 to 7, the graphic log corresponds to the original company descriptions (AND = andesite; GAB = gabbro; M = massive; OB = overburden; QFP = quartz-feldspar porphyry; QP = quartz porphyry; RHY = rhyolite; T.B. = tuff breccia), whereas the unit names (e.g., "Lemoine Diorite") are our interpretations. In figures 4 to 6, a five point moving average has been used for physical properties and average reflectance, whereas a three-point moving average has been applied to geochemical data.

Fig. 5. Downhole variations in major oxides in LEM-37 (corrected pXRF data). "L.D." is limit of detection.

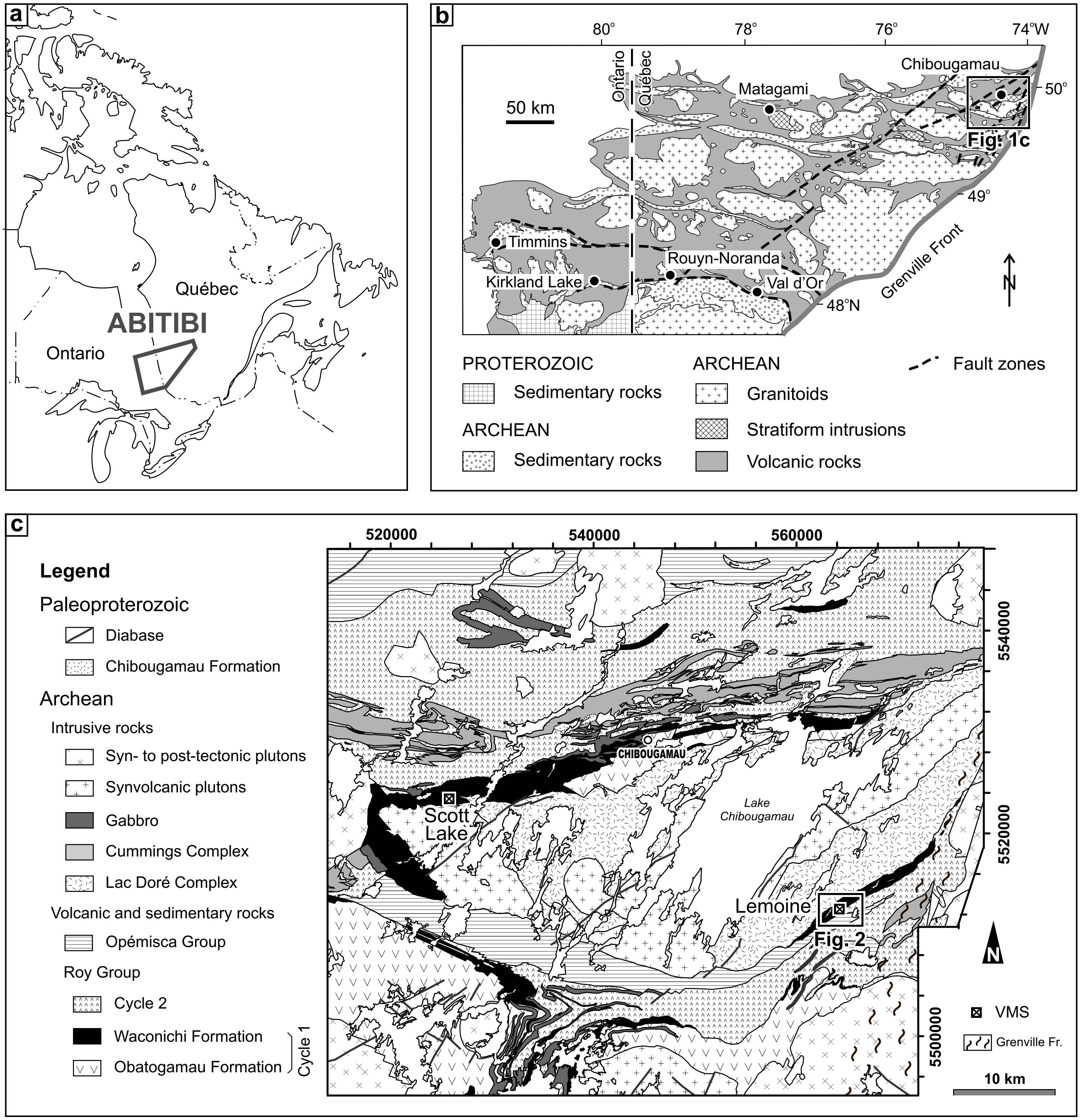
Fig. 6. Downhole variations in trace elements in LEM-37 (corrected pXRF data). "L.D." is limit of detection.

Fig. 7. Downhole variations in infrared mineralogy in LEM-37, interpreted automatically with the TSG Core software. In the plot of mineral groups, horizontal black lines show the main group detected at each depth whereas superimposed red squares are the subsidiary mineral groups. N.M.D. = no mineral detected. The Ishikawa alteration index (Ishikawa et al., 1976) and the chlorite-carbonate-pyrite index (CCPI; Large et al., 2001) have been calculated based on traditional geochemistry. Numbers 1-3 in the right margin represent alteration assemblages in the Lemoine Rhyolite, as described by Mercier-Langevin et al. (2014).

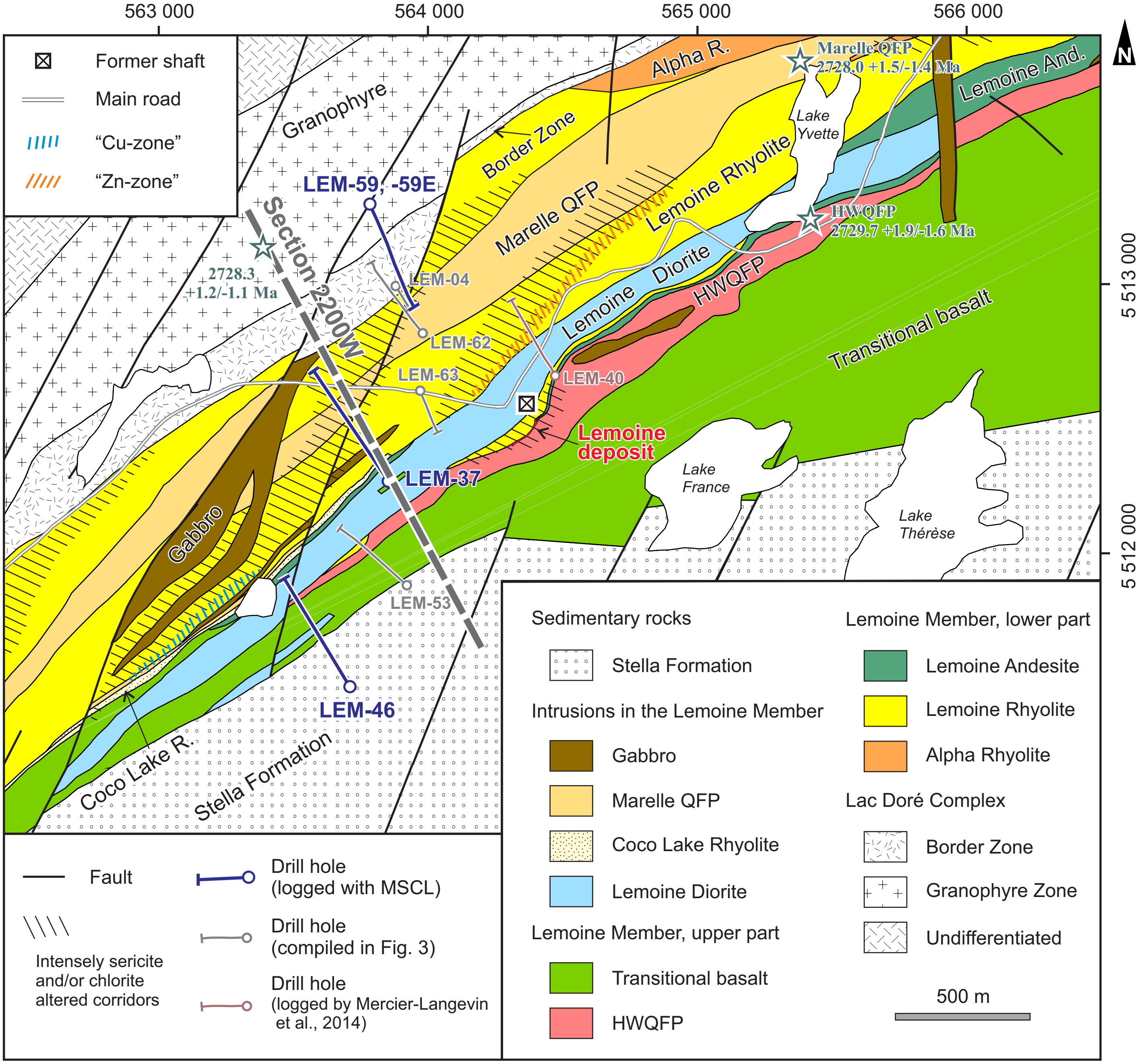
Fig. 8. Magmatic susceptibility versus density for a subset of the MSCL data in LEM-37. Only the data points assigned to the Lemoine Rhyolite, Coco Lake Rhyolite and Marelle QFP in the left margin of figure 4 are shown here for ease of visualization.

Fig. 9. Corrected pXRF data in LEM-37 (colored symbols, three-point moving average) plotted together with fields for certain geological units compiled in several drill holes from conventional analyses (grey outlines). (a) Volcanic rock classification diagram from Winchester and Floyd (1977). Note that TiO_2 is in weight percent whereas Zr is in ppm, divided by 10 000. (b) Ti/Zr versus Al/Zr (all elements in ppm). Note the good general correspondence between the corrected pXRF data and the conventional geochemistry, especially for the felsic units in (b). In this figure and figure 10, the data for the HWQFP has been omitted for clarity and "Gabbro1" corresponds to the interval 222.50-252.42 m, whereas "Gabbro 2" corresponds to the interval 834.85-863.69 m (see Fig. 4). Our interpretation is that there is no transitional basalt within LEM-37, but several dikes plot in that field. Data points color-coded as felsic units but plotting far from the main clusters for these units are interpreted as dikes.

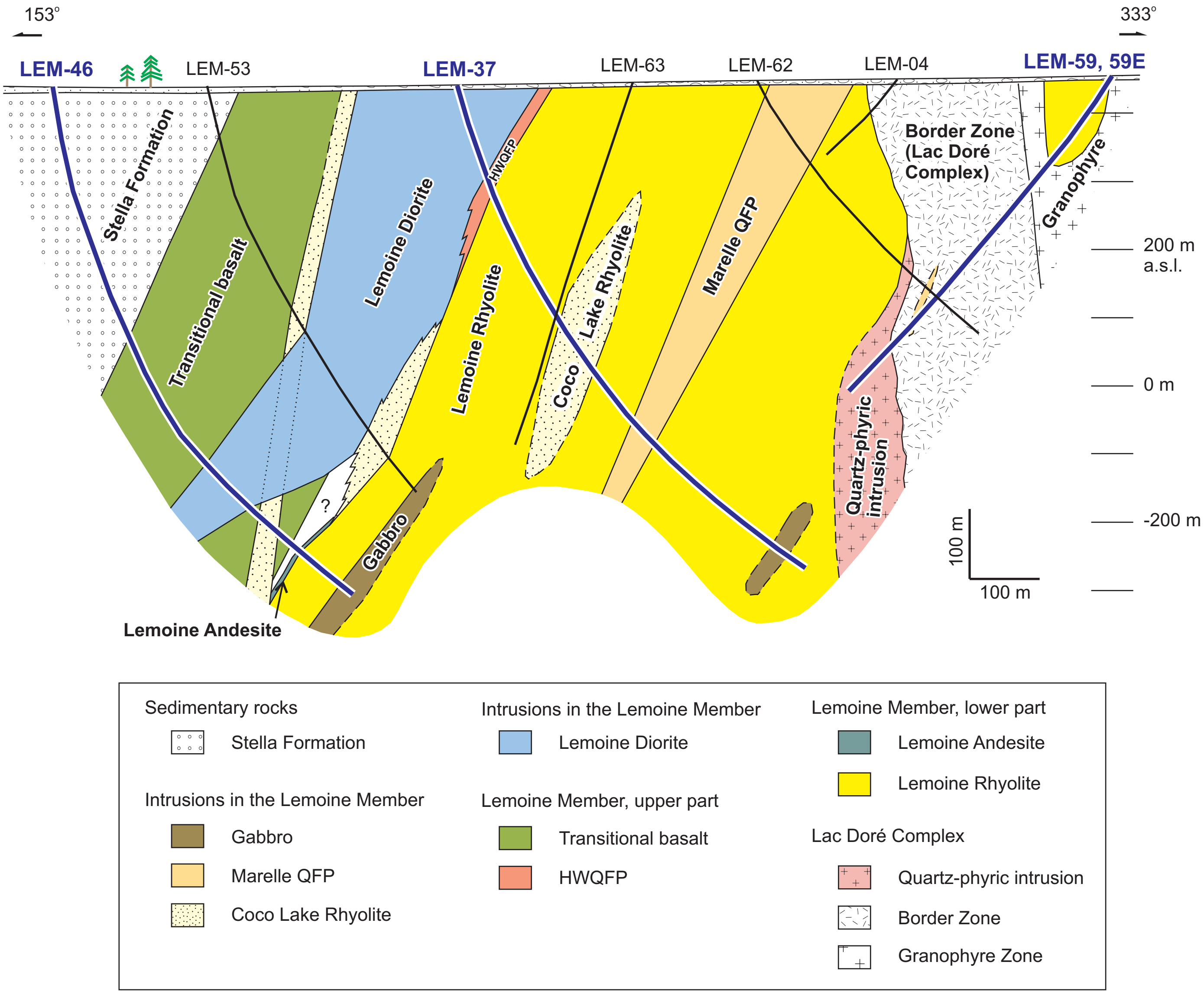
Fig. 10. Diagram of Zr versus Y, showing the corrected pXRF data in LEM-37 (colored symbols, three-point moving average) plotted together with fields for certain geological units compiled in several drill holes from conventional analyses (grey outlines). The boundaries between the different magmatic affinities are those of Barrett and MacLean (1999), for consistency with previous studies in the Lemoine area (Lafrance and Brisson, 2006; Mercier-Langevin et al., 2014).



Ross et al. Fig. 1



Ross et al. Fig. 2



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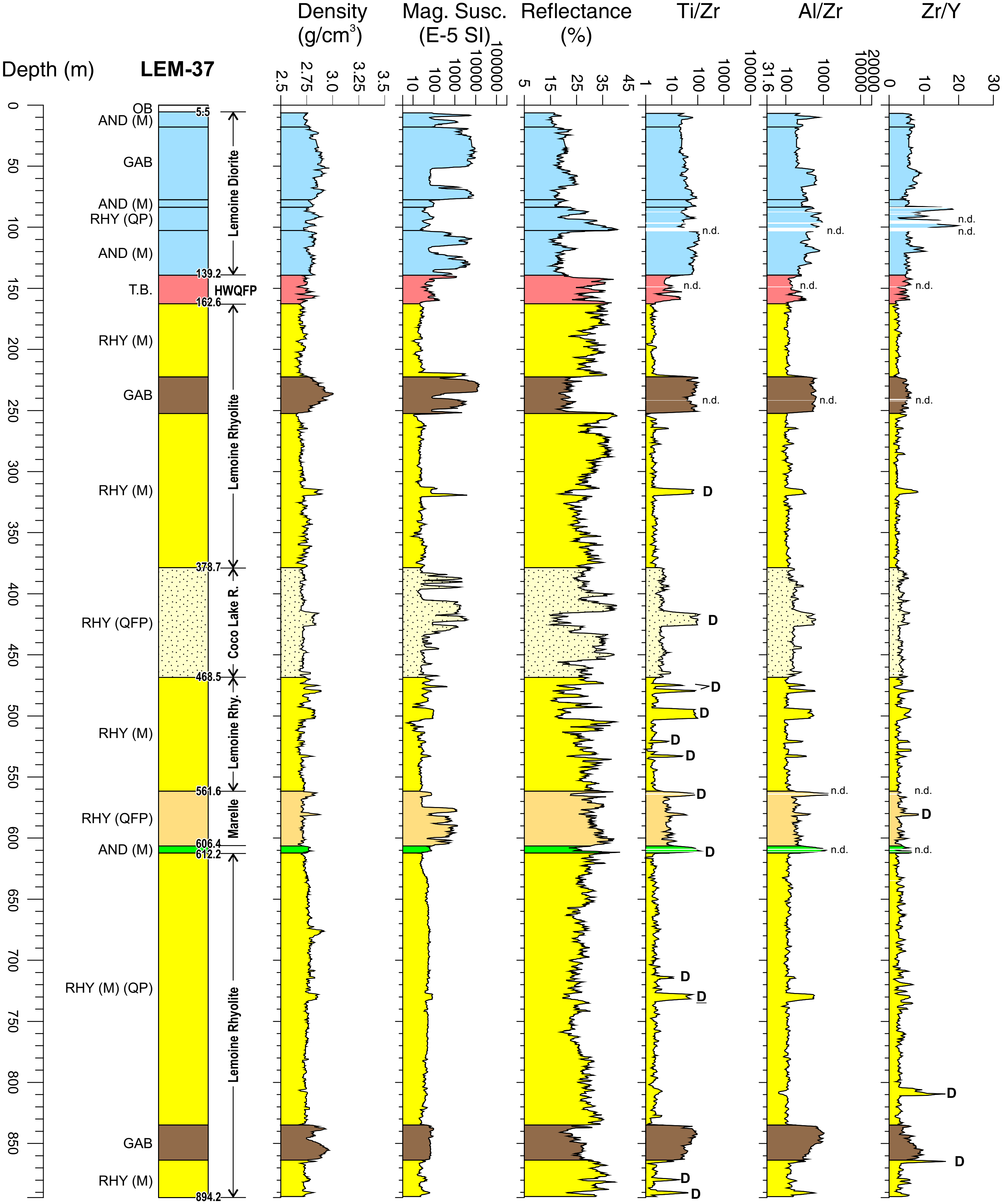

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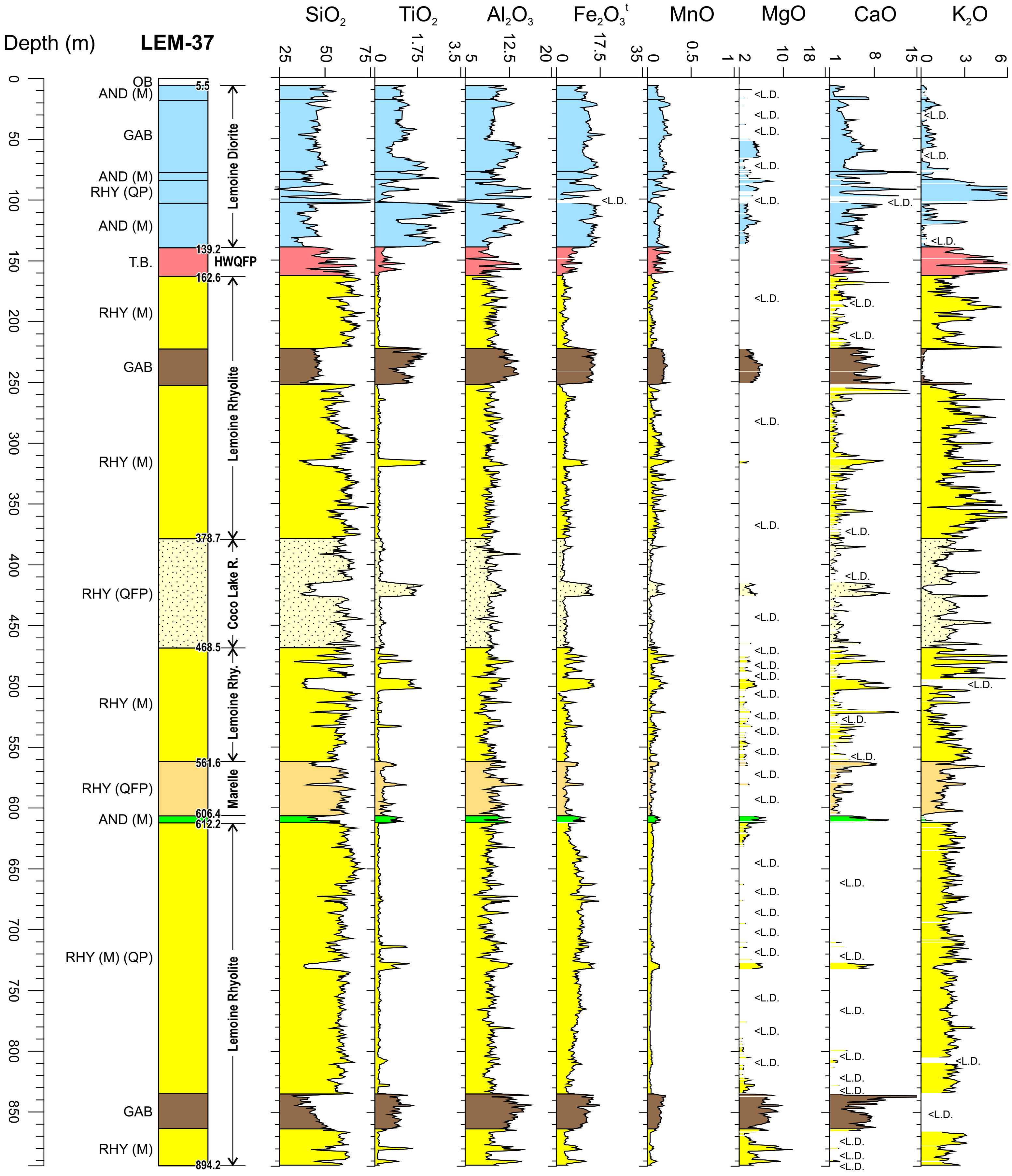

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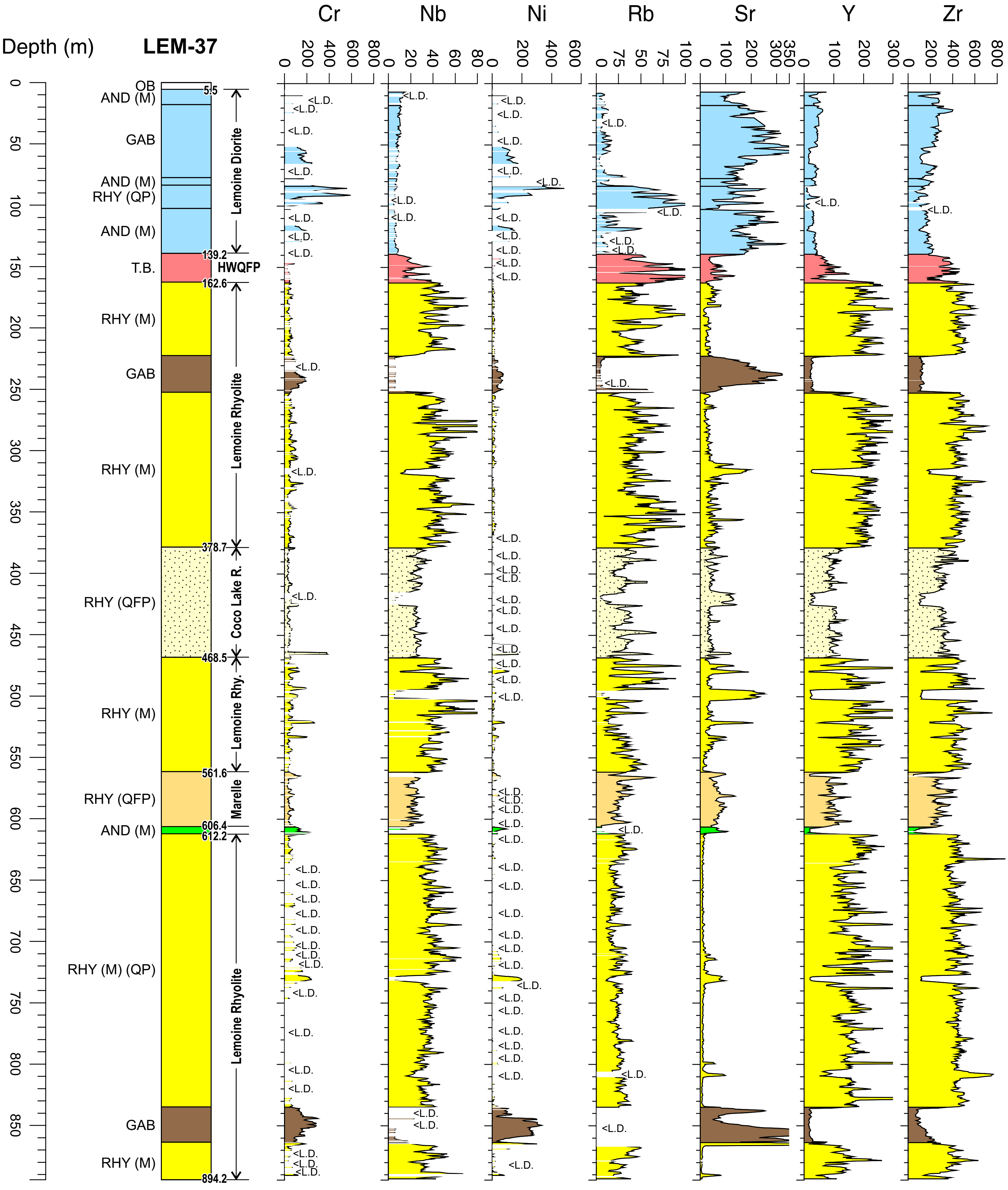

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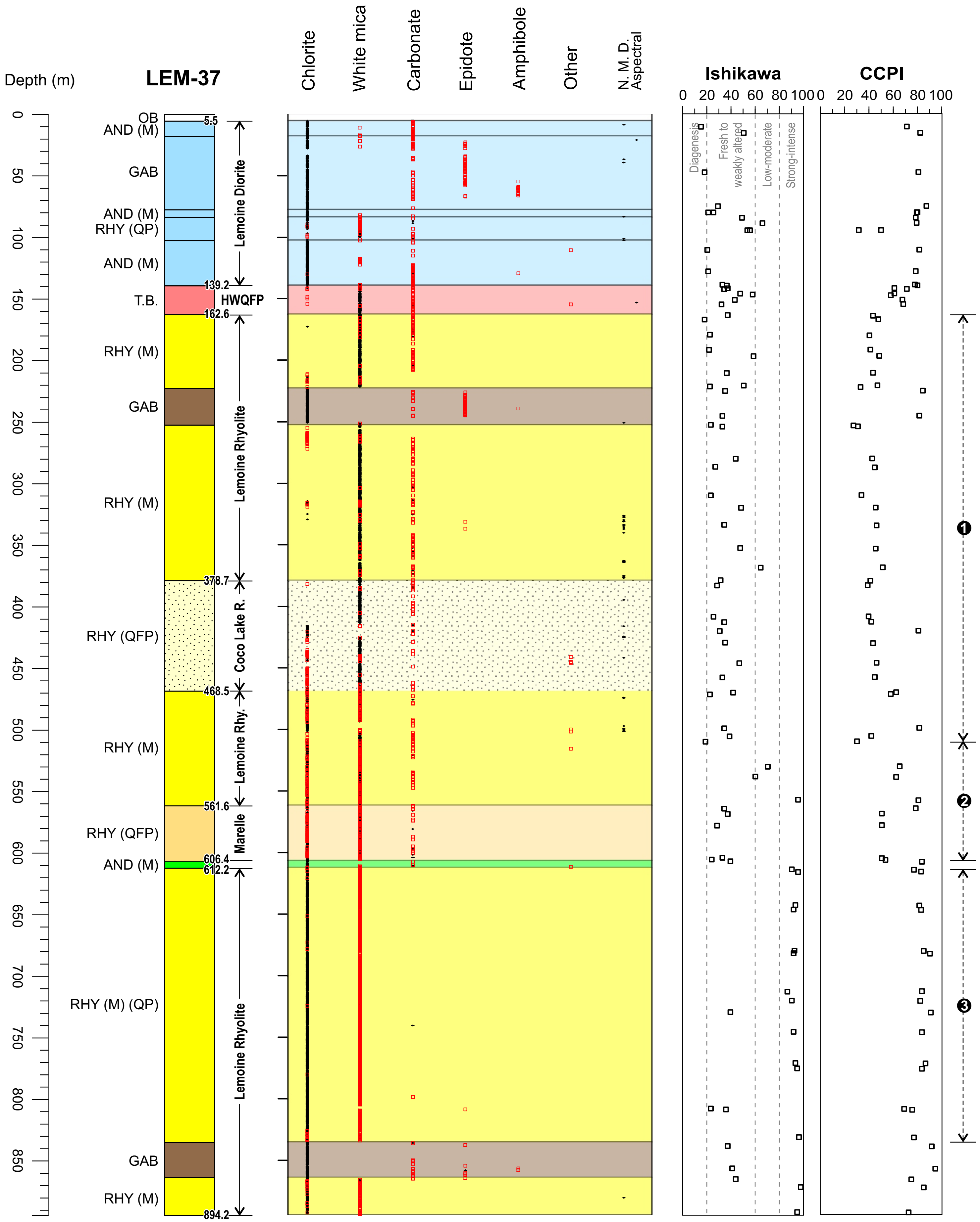

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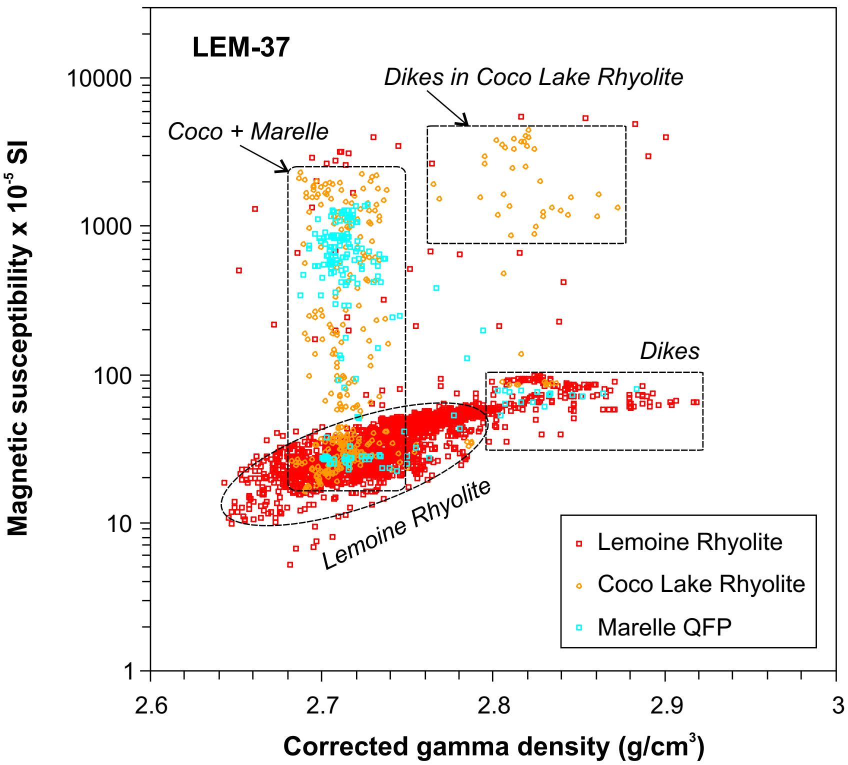

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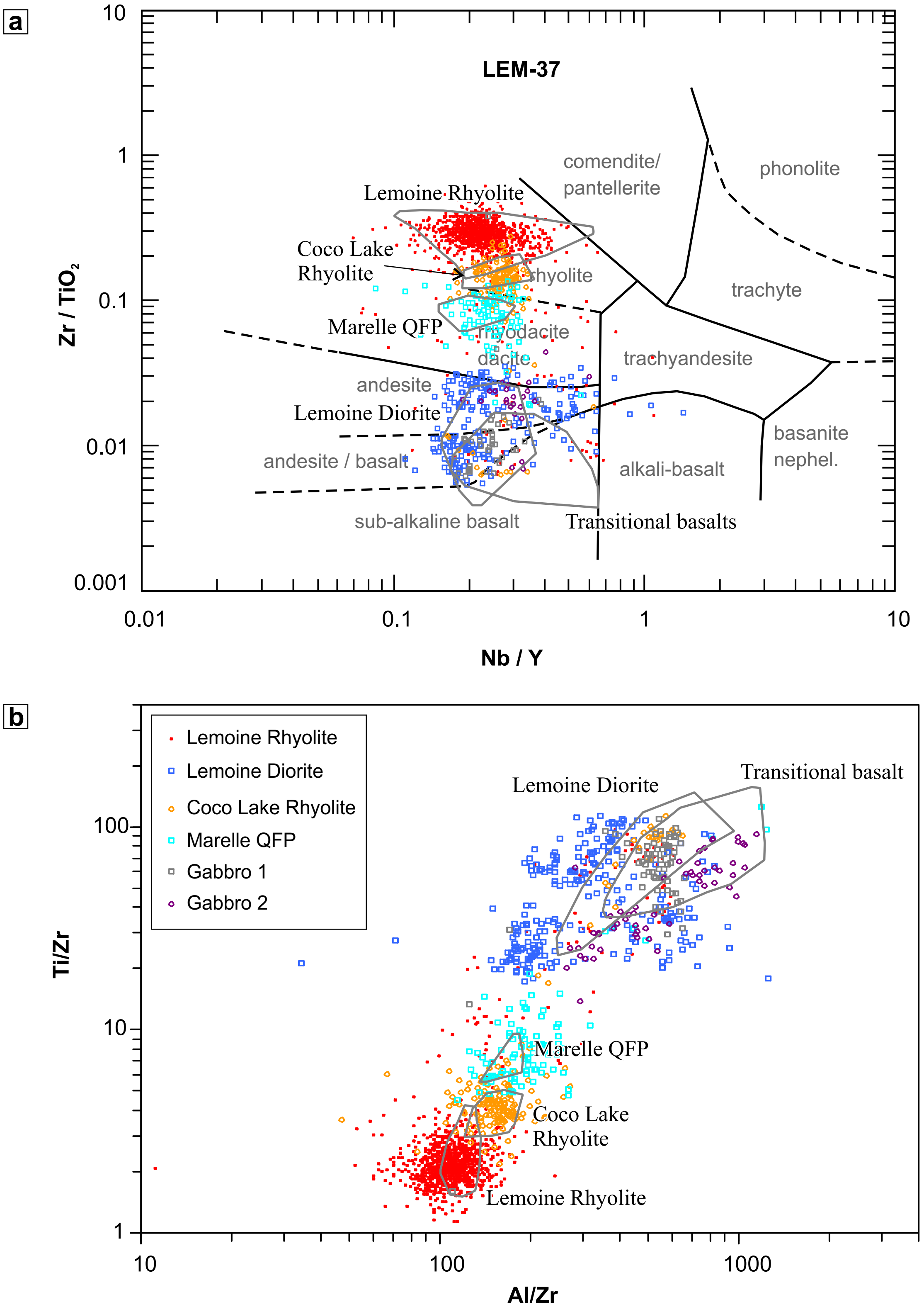

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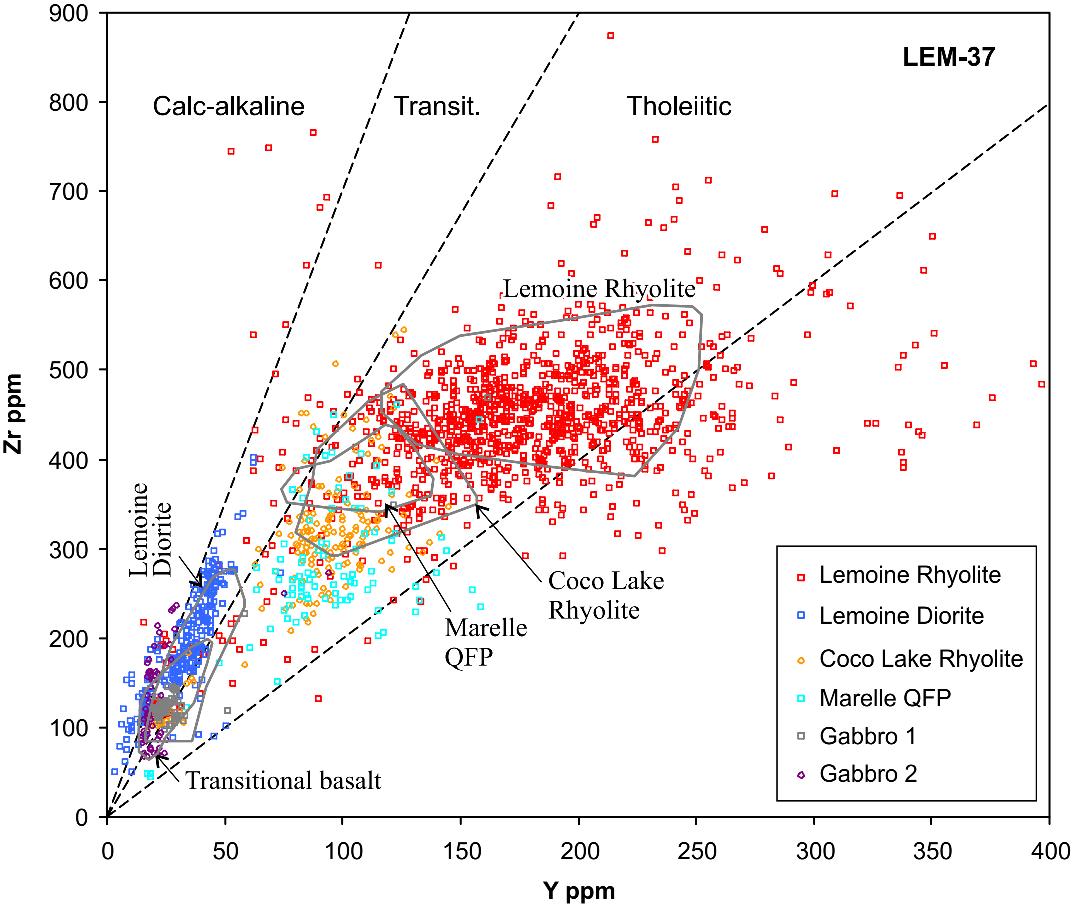

Ross et al. Fig. 10